

# Airborne Observation of the Hayabusa Sample Return Capsule Re-entry

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**NASA Ames Research Center and the SETI Institute collaborated on an effort to observe the Earth re-entry of the Japan Aerospace Exploration Agency's Hayabusa sample return capsule. Hayabusa was an asteroid exploration mission that retrieved a sample from the near-Earth asteroid Itokawa. Its sample return capsule re-entered over the Woomera Prohibited Area in southern Australia on June 13, 2010. Being only the third sample return mission following NASA's Genesis and Stardust missions, Hayabusa's return was a rare opportunity to collect aerothermal data from an atmospheric entry capsule returning at superorbital speeds. NASA deployed its DC-8 airborne laboratory and a team of international researchers to Australia for the re-entry. For approximately 70 seconds, spectroscopic and radiometric imaging instruments acquired images and spectra of the capsule, its wake, and destructive re-entry of the spacecraft bus. Once calibrated, spectra of the capsule will be interpreted to yield data for comparison with and validation of high fidelity and engineering simulation tools used for design and development of future atmospheric entry system technologies. A brief summary of the Hayabusa mission, the pre-flight preparations and observation mission planning, mission execution, and preliminary spectral data are documented.**

## I. Introduction

**T**HE design of atmospheric entry system technologies relies heavily on the use simulation tools of varying fidelity. Following initial trade studies using low-to-mid fidelity systems-level simulation tools, high fidelity computational fluid dynamics (CFD) simulations are used to define the aerothermal environment that an entry vehicle's thermal protection system (TPS) will experience. Coupled with material thermal response codes using appropriate boundary conditions, high fidelity simulations become powerful and sophisticated tools for the design and sizing of a vehicle's TPS that must withstand the anticipated entry environment. Supporting the development of

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these simulation tools are tests in tailored ground test facilities, such as hypersonic wind tunnels, shock tubes, and arc jets, that replicate aspects of the flight environment over a range of conditions and at appropriate time and length scales. Simulation capability gaps, uncertainty/sensitivity analyses, and mission element risk profiles guide test design and facility selection.<sup>1</sup> However, only partial duplication of the pertinent aerothermal processes is possible – even with multiple facilities and judicious experiment designs. Actual flight remains the benchmark for end-to-end validation of simulation tools.

NASA flight tests of instrumented entry vehicles at superorbital entry velocities have been few and were all from the Apollo program – most notably Fire II<sup>2,3</sup> and Apollo 4.<sup>4,5</sup> A complementary approach to instrumented entry vehicles is remote observation with optical instrumentation: the emission from an entering spacecraft and its surrounding gases provide insight into the aerothermodynamic processes of atmospheric entry and the performance of the capsule's thermal protection system. The Earth return of the sample capsule from the Japan Aerospace Exploration Agency's (JAXA) asteroid exploration mission Hayabusa presented a rare opportunity to gather these data via remote observation. Its return was the third, after NASA's Genesis and Stardust, sample return mission to re-enter Earth at superorbital velocities.<sup>6-8</sup>

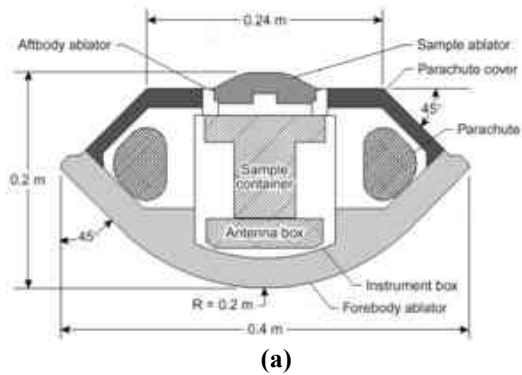
The primary objective of the Hayabusa airborne observation campaign was to obtain time-resolved measurements of absolute spectral irradiance from the capsule and its trailing wake. The data would be interpreted to reveal quantities of importance to atmospheric entry aerothermodynamics: apparent temperatures, shock radiation spectra, ablation species spectra (if present), and their temporal evolution during entry. The instrumentation suite, calibration procedures, and target acquisition and tracking strategies were designed to meet the primary objective while satisfying project constraints on budget, schedule, and risk.

NASA's utilization of airborne assets and spectral imaging instrumentation for observation of superorbital re-entry events traces its heritage to airborne astronomy and meteor observations. The observation aircraft flies at a nominal altitude of 12 km (approximately 39,000 ft), which is above 80% of the atmosphere and 99% of the atmosphere's water vapor. Almost all potential cloud cover is avoided at that altitude, and optical absorption due to atmospheric constituents is greatly diminished. Planning and execution of the observation mission followed similar experience with observation campaigns for NASA's Genesis<sup>6,7</sup> and Stardust<sup>8-19</sup> sample return re-entries and the destructive re-entry of the European Space Agency's ATV-1 (Automated Transfer Vehicle).<sup>20</sup> The optical instrumentation used on the aircraft tracked the capsule during its luminous period during re-entry and recorded temporally resolved spectra that were calibrated to absolute spectral irradiance. The observation yielded a comprehensive data set from multiple instruments with complementary and redundant capabilities.

The Hayabusa observation project was an international effort led by NASA Ames Research Center and the SETI Institute. Four other NASA centers, NASA Headquarters, JAXA, and collaborators from Australia and Europe also participated in the project. NASA Ames provided project management, mission planning, systems engineering, and pre-flight analyses. The SETI Institute was responsible for the science team (instrumentation) and mission planning. The NASA Dryden Flight Research Center's Aircraft Operations Facility (DAOF) provided the aircraft and services supporting its use for the observation mission. NASA Jet Propulsion Laboratory provided the observation mission planners with Hayabusa's trajectory that was used for developing the aircraft's flight path. The Space Meteorology Group (SMG) at NASA Johnson Space Center supported the team by providing weather forecasts for the region of South Australia where the re-entry occurred. Representatives of NASA Langley Research Center's HyTHIRM (Hypersonic Thermodynamic Infra-Red Measurements) airborne and ground-based re-entry imaging team were consulted regarding pre-flight mission planning. NASA Headquarters negotiated and secured an agreement to enable NASA/JAXA collaboration on the airborne observation. JAXA provided technical and operational data regarding the Hayabusa mission and sample return capsule re-entry. Researchers from the United States, Japan, Australia, Germany, and the Netherlands participated in the mission as members of the science team.

## **II. Hayabusa asteroid exploration mission**

The target of JAXA's Hayabusa mission<sup>21</sup> was the near-Earth asteroid Itokawa (1998 SF<sub>36</sub>), an S-type, Mars-crosser with a perihelion just inside Earth's orbit. Launched on May 9, 2003, from JAXA's Uchinoura Space Center, the Hayabusa spacecraft made contact with, and retrieved a sample from, Itokawa in November 2005. Because of the insignificant gravitational field of Itokawa, Hayabusa's heliocentric orbit was controlled to bring the spacecraft in the vicinity of Itokawa for exploration and sample collection. Hayabusa was to return its sample to Earth in June 2007. However, a series of communication and hardware malfunctions in late 2005 prevented the scheduled 2007 return. JAXA was able to restore communication in March 2006. By that time, JAXA had learned that fuel leaks from Hayabusa's chemical engines had forced the spacecraft off course and caused loss of attitude control. Two of its four ion engines had failed, along with two of its three reaction wheels. Despite these significant setbacks, JAXA



**Figure 1. (a) Schematic of Hayabusa sample return capsule. (b) Photograph of assembled sample return capsule. Courtesy of JAXA.**

to NASA's Genesis and Stardust missions, Hayabusa's sample was packaged into an Earth entry vehicle, or sample return capsule (SRC), for transit through the atmosphere and recovery. Hayabusa's SRC was a 45° sphere cone with a diameter of 40 cm (Fig. 1) and a mass of 16.3 kg. The SRC's thermal protection system was made entirely of carbon phenolic. JAXA obtained permission from the Australian government to utilize the country's Woomera Prohibited Area (WPA) in South Australia for landing and recovery of Hayabusa's SRC. The WPA is used for defense and aerospace testing and evaluation. The Australian Aerospace Operations Support Group (AOSG) assisted JAXA with preparations for the June 13, 2010, return and subsequent recovery of the SRC. Beginning in April 2010 and using the remaining ion engine, Hayabusa executed five trajectory correction maneuvers (TCMs) to target the WPA.

The SRC was released from the spacecraft three hours prior to re-entry. This time interval was chosen by JAXA so as to maintain power to the sample canister for thermal management. Because the spacecraft had lost chemical propulsion capability earlier in the mission, it could not be diverted from its trajectory following release of the capsule. It therefore entered the atmosphere along nearly the same corridor as the SRC and was destroyed during re-entry. The capsule ejection mechanism did impart a small separating velocity that, over the three hours, widened the distance between the SRC and the spacecraft.

The SRC was successfully recovered following re-entry. In the following months, JAXA was able to definitively conclude that a small amount of material discovered in the sample canister was from Itokawa. The success of Hayabusa has enabled JAXA to proceed with a second sample return mission, Hayabusa II, that is scheduled to launch in 2014.

### III. Observation campaign elements and mission planning

Development of the mission plan for the Hayabusa observation campaign relied on the expertise of several disciplines: aerothermodynamics, metrology, systems engineering, and aircraft operations for the technical aspects of the observation mission; staff at NASA Headquarters specializing in international relations secured the necessary agreement for cooperation between NASA, JAXA, and other international partners. The observation mission project and implementation plans were developed starting in late September 2009. Hayabusa SRC trajectory analysis, flight path planning, target acquisition strategy, and instrument suite selection were the four primary technical tasks that had the greatest impact on mission success. Just as important were logistical and administrative tasks that enabled the mission to proceed on schedule to meet the June 13, 2010, re-entry date and time.

The mission preparation activities documented in this section were reviewed by the NESC and NASA Dryden prior deployment. The primary purpose of the NESC review was for subject matter experts within the agency to assess and evaluate the mission's objectives, methods, and risk mitigation strategies. The Dryden reviews were primarily concerned with operational readiness and safety. All reviews had been completed prior to the target June 1, 2010, deployment date at the DAOF.

#### A. Re-entry trajectory and aerothermal environments analysis

For our purposes of planning the airborne observation, the re-entry trajectory and aerothermal heating to the Hayabusa SRC were examined using *TRAJ*, a trajectory analysis tool.<sup>22</sup> *TRAJ* computes the trajectory from entry interface to 25 km altitude using a three degree-of-freedom simulation. The trajectory analysis portion of *TRAJ* incorporates gravitational, atmospheric, and aerodynamic models. The entry state vector, nominally at 200 km

was able to execute a series of trajectory corrections to target Earth for arrival in June 2010 using a combination of cold xenon gas ejections from the ion engines, solar pressure, and thrust from the remaining ion engines.

Hayabusa was the world's third extraterrestrial sample return mission. Similar



**Figure 2. Overview of Hayabusa SRC re-entry trajectory into the Woomera Prohibited Area, South Australia. The dominant portion of the re-entry heat pulse is highlighted in red. Also shown is the DC-8's flight path to and from the observation way point. The path flown during the re-entry event is highlighted in green.**

altitude, and entry vehicle properties (dimensions, mass, orientation) are provided as inputs. The stagnation point convective and radiative heat fluxes are computed using engineering approximations with equilibrium thermodynamics and transport property models. *TRAJ* can also compute the stagnation point temperature using the *FIAT* (Fully Implicit Ablation and Thermal) TPS material response code.<sup>23,24</sup> While the material properties of Hayabusa's carbon phenolic were not known, an adequate approximation was made using properties from NASA's TPSX materials database.\* The predicted surface temperature time history, indexed to the re-entry trajectory (latitude,

longitude, altitude, time), provided a baseline with which key parameters of the airborne observation mission were defined through trade studies.

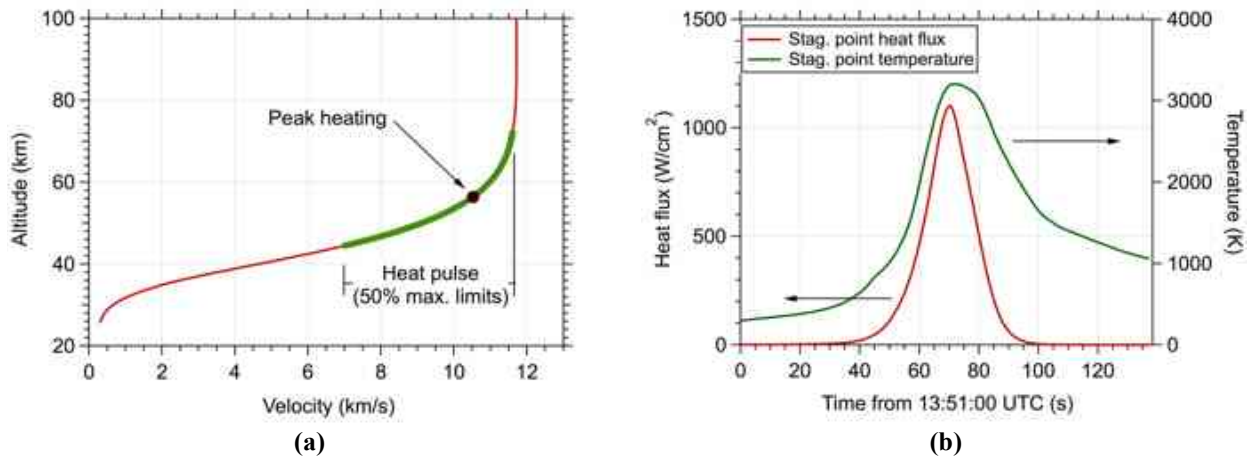
The nominal entry state vector was obtained initially from JAXA. The inertial entry speed and angle of the nominal trajectory were 12.2 km/s and  $-12.3^\circ$ . The entry was ballistic (zero angle-of-attack). An aerial overview of the nominal SRC re-entry trajectory as seen from south of the ground track is shown in Fig. 2. Figure 3a) shows an altitude-velocity profile of the trajectory. The time histories of the stagnation point heat flux and surface temperature are shown in Fig. 3b). Peak heating was predicted to occur at approximately 57 km altitude, or approximately 68 s from the entry state vector datum, which begins at an altitude of 202.03 km and time of 13:51:12 UTC. Entry interface at 121.9 km (400 kft) was predicted to occur at approximately 13:51:46 UTC (11:21:46 pm local).

The predicted peak Hayabusa heat flux value computed with *TRAJ* slightly exceeds that predicted from high-fidelity simulations for the Stardust SRC.<sup>12</sup> The predicted peak temperature was approximately 3200 K, which was similar to the value for predicted for Stardust from post-flight CFD/FIAT analysis.<sup>12</sup> The two SRC re-entries share more similarities than differences. These similarities were reflected in the predicted optical phenomena<sup>10</sup> and the planning and execution of the two airborne observation campaigns.

The SRC's descent through the atmosphere produced optical emission from the SRC's surfaces, the high-temperature gases surrounding the vehicle, and gases and dust in the vehicle's wake. The surface emission is thermal in origin and has an assumed graybody spectrum whose magnitude characterized by the surface's temperature and emissivity. The gas emission originates from the excited states of atmospheric air species and other gas-phase species, such as CN, originating from heat shield ablation products injected into the vehicle's boundary layer. The excited states are populated by the extremely high temperatures of the shock layer between the shock wave and vehicle surface. These states emit in discrete spectral lines and bands characteristic of their atomic or molecular structure. The intensity of the gas radiation depends on the number densities of the emitting states and spectroscopic factors that govern their radiative properties. Wake radiation, when present, originates from species with long-lived excited states, also populated by shock heating, that have become entrained in the wake of the vehicle. Thermal radiation from the SRC surface was expected to dominate the emitted spectrum.

Due to the small size of the SRC and the distance between the SRC and the observing aircraft, the imaging instruments on board the aircraft were unable to distinguish spatial distributions of the emitted SRC surface and surrounding gas radiation; the SRC appeared to the instruments as a point source of light. Therefore, the apparent magnitude and spectra of the observed emission signatures were weighted by the relative magnitudes of the gas and surface radiation and spatial integration of their distributions. The apparent magnitude is also a function of the time-

\* <http://tpsxnasa.gov>



**Figure 3. (a) Altitude vs. velocity of Hayabusa SRC re-entry trajectory. Maximum total heat flux occurs at approximately 57 km altitude. (b) Temporal profiles of SRC stagnation point heat flux and temperature computed using *Traj* (see text).**

dependent slant range (the distance between the SRC and aircraft), since the irradiance of a source scales with the inverse square of distance. Finally, the magnitude and spectra are also attenuated by absorption due to atmospheric constituents, primarily water vapor and ozone, and by scattering from nitrogen and oxygen molecules. The estimated magnitude was used in system trades for establishing the observation aircraft's flight path, configuring instrument sensitivity settings, and defining instrument calibration source specifications. At peak heating, the apparent magnitude as seen from the aircraft was predicted to be approximately -6, a brightness similar to Venus.

## B. Aircraft

The aircraft used for the observation was NASA's DC-8 Airborne Laboratory. The aircraft's range, payload integration capabilities, and optical access made it well suited for the Hayabusa re-entry observation. This aircraft, along with several other NASA airborne assets, is based out of the NASA's DAOF in Palmdale, CA. The DC-8-72 has a range of 10,000 km (5,400 nmi) and flight endurance of 12 hours. The service ceiling is 12.5 km (41,000 ft). The maximum cruising speed is 890 km/h (480 knots). The 15-person mission crew included mission directors, flight crew (pilots, navigators, flight engineers), mechanics, and technicians, and an operations engineer. The DC-8 was used to study meteor showers and for the Stardust and ATV-1 re-entry observation campaigns.

## C. Instrumentation

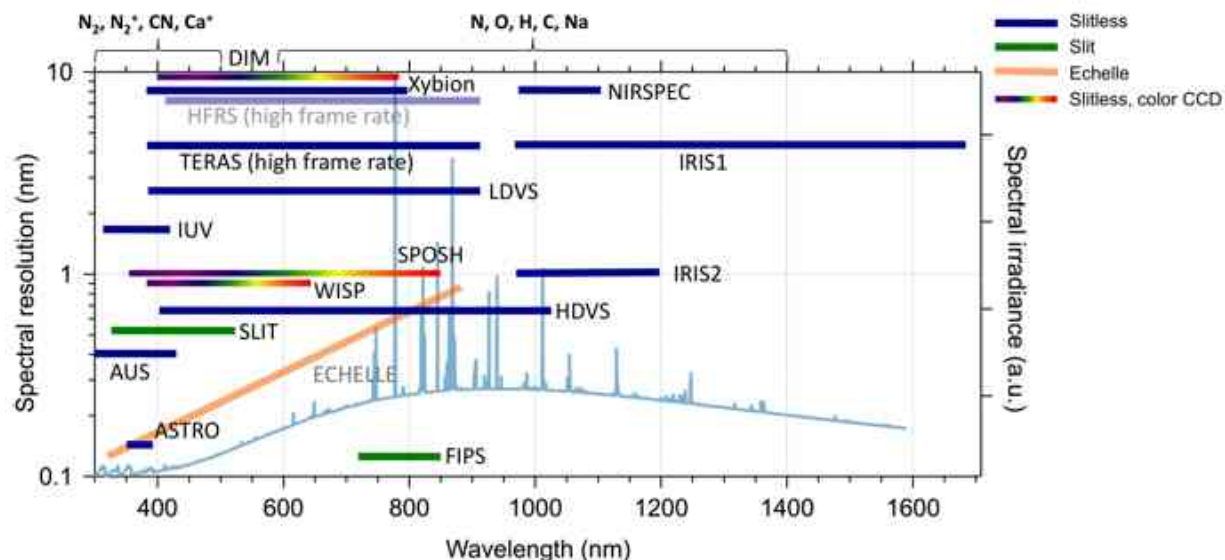
The DC-8 affords ample space for multiple optical instrument platforms with a variety of technical capabilities. The instruments were chosen based on their specifications, flight heritage, and experience of the operators. The use of multiple instruments with overlapping spectral ranges and other performance characteristics was intended to mitigate potential data loss due to instrument failure and target acquisition/tracking failure.

A total of 25 science instruments were placed on the aircraft. Many instruments were slitless spectrographs that utilized transmission gratings. Other instruments employed fiber-coupled slit spectrographs or cameras with band pass filters to realize spectral resolution. Three instruments were devoted to high resolution color video documentation. Table 1 shows the specifications of the instrument suite. The first section of the table lists the spectrally resolving instruments, while the last section lists the imaging instruments. The names of the instruments are acronyms or abbreviations used principally by the team for management purposes. The spectral range and resolution of the spectrally resolving instruments are shown graphically in Fig. 4. Spectral coverage was from the near ultraviolet through the short wave infrared (up to 1670 nm). Three instruments used color-sensitive imaging arrays, yielding colored (rather than grayscale) images of the dispersed spectra. Figure 4 also shows a predicted spectrum, computed using the NEQAIR radiation transport code,<sup>25</sup> as seen from the aircraft. This spectrum is the sum of the surface radiation from the heat shield and atomic and molecular radiation from the shock layer ahead of the capsule. Though not included in the computed spectrum, emission from C, H, CN, and other products of the ablating heat shield would also appear in the spectral range of the instrument suite.

A camera with a transmission grating simultaneously recorded an image and dispersed spectra of the light radiated by the capsule, shock-heated gas, and trailing wake. The technique, often used in astronomy, is appropriate for singular or sparse point sources within the camera's field of view. The transmission grating is placed in front of a

**Table 1. Instrumentation suite.**

Instrument	Wavelength (nm)	Resolution (nm)	Frame rate (Hz)	Application
ASTRO	370-410	0.18	0.5	Very high resolution near-UV
AUS	300-420	0.4	10	Intensified near-UV
DIM	440-700	10.0	1	Broadband photometry (R,G,B)
ECHELLE	336-880	0.12-0.90	10	High resolution near-UV to NIR (Echelle spectrograph)
FIPS	727-826	0.2	30	Very high resolution NIR (Fabry-Perot interferometer)
HDVS1, HDVS2	380-900	0.75	30	High resolution visible
HFRS	420-900	4.0	1000	High frame rate visible
IRIS1	960-1670	4.5	30	Low resolution NIR to SWIR
IRIS2	960-1670	1.0	30	High resolution NIR to SWIR
IUV	320-440	1.9	30	Intensified near-UV
LDVS	380-900	2.5	30	Low resolution visible to NIR
NIRSPEC	960-1100	0.56	30	high resolution NIR
SLIT	320-520	0.53	10	High resolution near-UV to visible (slit spectrograph)
SPOSH	380-900	1.0	1	Wide field visible to NIR
TERAS	380-900	2.0	500	High frame rate visible to NIR
WISP	380-800	0.9	1	Wide field visible
Xybion-2	380-800	8.2	30	Intensified low resolution visible
ALLSKY	400-700	-	30	Wide field from zenith port
INI	1500-1670	-	1	Narrowband SWIR
JAXA	400-770	-	30	Filtered broadband (four cameras)
RED1, RED2	380-900	-	24	Digital cinematography
THDTV	400-770	-	30	High definition television
Xybion-1	380-800	-	30	Intensified CCD



**Figure 4. Spectrograph instrumentation used for airborne observation. Most instruments were slitless spectrographs that used transmission gratings. The predicted spectrum at peak heating as seen from the aircraft is also shown.**

camera's objective lens. A zero-order image of the point source passes directly through the grating to the camera's image plane. The diffracted (spectrally resolved) orders are displaced from the zero order image on the image plane. The spatial displacement between the directly transmitted (zero order) and diffracted orders on the image plane, determined by instrument parameter selection, grating orientation, and wavelength calibration, enable recovery of spectra from the point source.

Each instrument platform, which in some cases accommodated more than one science instrument, was assigned to a viewport of the DC-8. Most instrument viewports used on this mission were modified passenger windows on the port side of the aircraft. Depending on the science instrument's requirements, special flat windows made of optical quality materials, such as borosilicate glass or fused silica, were installed in the viewports. The viewports have clear apertures up to 40.6 cm (16") diameter or width. Platforms are mounted to ball heads positioned close to the viewports. The ball head location enables a platform's line-of-sight to sweep through the largest angles bounded

by the viewport's frame. The cold window surfaces are prone to condensation at high altitudes, so a forced stream of cabin air was directed over the viewports when needed to diminish this possibility.

An instrument platform consisted of one or more science instruments and a target acquisition/tracking camera. The acquisition and tracking cameras, typically small-format, low-resolution CCDs, have wider fields of view compared to the science instruments. When installed, the line of sight of the science instrument is aligned to coincide with the line of sight of the acquisition/tracking camera. The acquisition/tracking cameras were sensitive enough to render star fields of magnitude +6 or fainter. The instrument platforms were typically attached to rails on the cabin wall mounted below the viewport windows. Some platforms were attached to the seat rails on the cabin floor. Auxiliary equipment and data acquisition computers were mounted to racks attached to the seat rails.

Each instrument platform required two team members: the *platform tracker* manually tracked the SRC while the *instrument operator* operated the data acquisition and instrument control systems. The platform tracker wore a video headset with a feed from the platform's acquisition/tracking camera. The instrument operator ensured that the science instrument's data system was acquiring signals from the target. The science team was composed of 27 members, each of which had tracking or instrument operation responsibilities.

The DC-8 is equipped with an IRIG (inter-range instrumentation group) timecode generator that is synchronized to the aircraft's global positioning satellite receiver. All instrument platform data acquisition systems had one or more methods to record universal time from the generator's IRIG-B timecode reference concurrently with their data streams. The timecodes were necessary to synchronize the instrument data streams with each other as well with other time-accurate sources outside of the aircraft. Aircraft navigation and performance data were also available to the instrument platforms through an on-board network.

The science instruments were calibrated to yield measurements in units of absolute spectral irradiance ( $\text{W}/\text{m}^2 \text{ nm}$ ). An instrument's response function is used to convert the measured signal magnitude to absolute irradiance. Each instrument's response function was determined from magnitude measurements of a source of known spectral irradiance. Generally, the response function depends on wavelength of the incident light, position on the image sensor, and instrument sensitivity settings (detector gain, exposure time). The reference sources used for these measurements were two quartz-tungsten-halogen integrating spheres with NIST-traceable absolute radiance calibrations. Calibration measurements were performed before and after the re-entry observation. Application of the response function and corrections for slant range distance (between the capsule and aircraft) and atmospheric extinction would be performed during data reduction.

#### **D. Flight path planning**

The prime objective to be realized with the design of the DC-8's flight path was to capture SRC emission from first detection through peak heating and, preferably, beyond. The systems engineering team required reliable and timely information regarding Hayabusa's trajectory – most importantly the trajectory's entry state vector – for mission planning purposes. The team conducted trade studies to obtain an optimized flight path solution that maximized signal quality, minimized risks with target acquisition and tracking, accommodated potential trajectory dispersions, and complied with technical and administrative constraints. The flight path planning methodology for this mission is described in detail in Reference 26.

The primary technical challenges for the observation were target acquisition and optical tracking of the SRC. That, in turn, required knowledge of when and where the capsule would first appear against the night sky, along with the path that the capsule would travel. Navigators from NASA JPL provided the Hayabusa entry state vector that was used to design an optimum flight path and acquisition strategy. The JPL navigators updated the entry state vector following each successive TCM.

The administrative constraints on flight path planning were primarily related to safety. A keep-out zone, defined by 60 km-wide corridors on each side of the SRC's ground track (120 km wide total), limited the point of closest approach to the trajectory by the aircraft. The WPA is a region of controlled airspace. While a grant of temporary reserved airspace was possible, enabling the DC-8 to enter the WPA, it was determined to have added marginal value to the chosen flight path that stayed within civil airspace. However, a second flight path within the WPA was designed as an alternate if weather conditions prevented use of the primary path. June 13, 2010, was a moonless night, so there was no limitation on sight line placement due to direct or reflected glare from moonlight.

Since the spacecraft bus could not be diverted following SRC separation, there was concern that debris fragments from the destructive re-entry of the bus would obscure a clear view of the SRC unless the two were well separated spatially at the time of re-entry. Bus fragments were predicted to be much brighter than the SRC up until the point where the spacecraft had largely disintegrated. SRC tracking efforts would be challenging without an unambiguous target. Reducing the impact of the potentially small separation between the bus and SRC was not realistically possible given the objectives and other constraints on flight path planning. However, the bus was

expected to break up high in the atmosphere and would enable early identification Hayabusa's re-entry for target acquisition.

Once the optimum flight path was determined, the systems engineering team generated star charts with a superimposed SRC trajectory as seen from the aircraft. These charts were used by the instrument platform trackers so they could learn where – and when – Hayabusa was predicted to appear in the night sky. The as-flown flight path for the observation is shown in Fig. 2.

#### **E. Logistics and schedule**

The observation campaign deployment spanned three phases: upload, mission execution, and download. Most instrumentation used on the aircraft was delivered to the DAOF in advance of the arrival of the science team. The DC-8 was made available to the science team for instrument installation and integration. Tasks included assembling camera mounting hardware, populating instrumentation racks, and establishing data links between the instrument platforms and the DC-8's flight data and network services. The instrument platforms were required to be stored for take off and landing. Their configurations were designed for rapid assembly and breakdown while airborne. Instrument racks attached to seat rails were provided for use by the science team. Large bins attached to seat rails and overhead lockers were used to store all other instrument platform equipment that needed to be assembled after take off. The DC-8 mission crew performed weight and balance checks on the aircraft to ensure that the instrumentation payload was within flight certification limits. Prior to departure for Australia and upon return, the science team acquired data for wavelength and irradiance calibration of the science instruments. Calibration measurements were also obtained from known astronomical targets while en route.

The forward base of operations for the Hayabusa re-entry observation was Melbourne Airport (MEL), the international airport for Melbourne, Australia. The transit flights between Palmdale to Melbourne required crew rest and refueling stops at Hickam Air Force Base in Honolulu, HI. The station point for the observation was approximately 1140 km (615 nmi) from Melbourne. The mission team arrived in Melbourne early in the morning of Friday, June 11, 2010. The team was deployed in Melbourne from June 11 to June 15.

Once in Melbourne, the science team performed further instrument checks and updated the flight path based on the most current Hayabusa trajectory. A practice flight the evening of Saturday, June 12, 2010, was performed as a dress rehearsal. The flight gave the flight crew and science team the opportunity to rehearse procedures and follow timing cues for the actual re-entry observation flight the next night. A crucial objective of the rehearsal was for the instrument operators to become familiar with night sky star field in which Hayabusa was expected to appear.

### **IV. Mission execution and preliminary results**

The capsule was commanded to be released from the spacecraft bus at 10:51:00 UTC (June 13, 2010). Successful separation was confirmed by JPL through analysis of tracking data and reported to the observation team just prior to departure from Melbourne at 11:35 UTC (9:35 pm local). The transit flight to the vicinity of the observation racetrack was approximately 80 minutes. During transit, the science team removed their instruments from storage and assembled them for data collection. The pilots entered the planned flight pattern of the observation racetrack on a northeast heading. Two circuits of the racetrack were completed to synchronize timing for the aircraft to pass through the initial waypoint of the observation leg. The passes along the observation leg of the two pre-entry circuits gave the platform trackers the opportunity to re-familiarize themselves with the star pattern of the region of the sky where the spacecraft was predicted to appear. At 13:49:19 UTC, the DC-8 pilot crossed the planned waypoint at the start of the observation leg.

A timing script prepared by the mission planners was read by the DC-8's navigator during the re-entry. The script called out the sequence of events at their predicted times, such as first appearance, peak heating, and maximum deceleration, as cues to the platform trackers. The luminous destructive re-entry of the spacecraft bus first appeared at approximately 13:51:49 UTC. All airborne instruments were able to acquire and track the spacecraft by approximately 13:52:00 UTC when the spacecraft was at a distance of 425 km from the aircraft. Fortuitously, the separation distance between the spacecraft debris and the SRC was sufficient for the airborne instruments to spatially discriminate the two by 13:52:00 UTC – the SRC appeared ahead of and below the spacecraft debris. Peak heating was predicted to occur at 13:52:20  $\pm$  2s UTC. The capsule was tracked until 13:53:03 UTC, at which time the capsule was approximately 100 km from the aircraft. The total observation time from first detection to loss of signal was approximately 70 seconds and corresponded to the SRC's descent from approximately 85 km to 35 km. Twenty three of the 25 science instruments successfully recorded data; two instruments (Echelle and HFRS, see Table 1 and Fig. 4) failed due to operational errors.





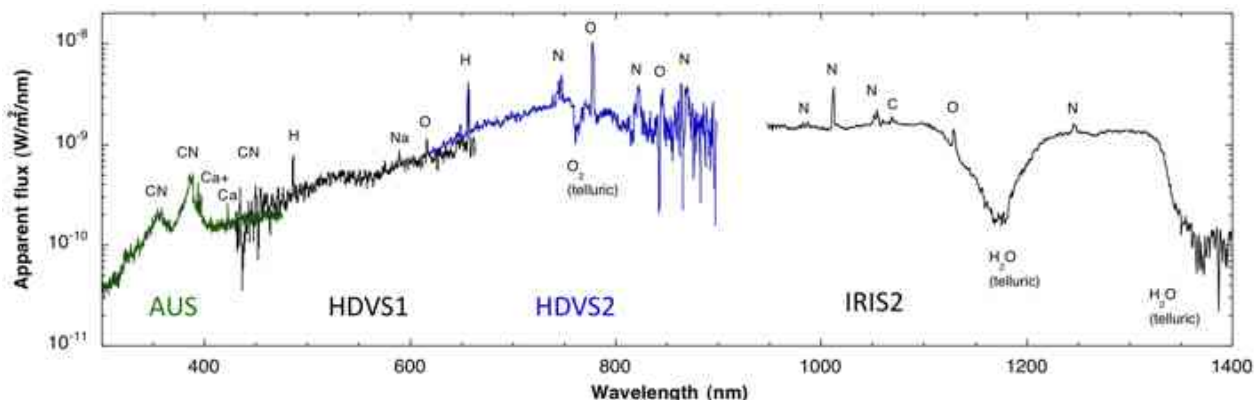
**Figure 5. Sequence of images of Hayabusa’s SRC and the destruction of the spacecraft bus. The SRC can be seen in the lower right of each image. See text for details.**

airborne laboratory observed the re-entry of the Hayabusa SRC on June 13, 2010. The DC-8’s flight path was engineered and flown to provide a view of the spacecraft that bracketed the heat pulse to the capsule. Twenty two imaging instruments on board the DC-8 successfully recorded the luminous portion of the re-entry event. Preliminary, qualitative analysis of spectral data of the capsule clearly indicate the presence of shock heated air species and carbon-bearing species from heat shield ablation. Data reduction and analysis and comparison with comprehensive high-fidelity simulations will follow in the coming months.

Figure 5 shows a series of frames from the science team’s highest resolution camera (RED1). The sequence spans approximately 25 seconds from 13:52:03 UTC, during which time the spacecraft bus largely disintegrated. While the high resolution video imaging data were processed for rapid dissemination, reduction and calibration of the spectrographic data sets are in progress as of this writing and are not complete. However, preliminary results have been examined for qualitative features and trends. The preliminary data in Figure 6 show a composite capsule spectrum from four instruments (AUS, HDVS1, HDVS2, IRIS2) at 13:52:17.27 UTC. At that time, the capsule was approximately 250 km from the aircraft. The individual spectra have been calibrated to absolute spectral irradiance and corrected for this slant range distance. The spectrum has not been corrected for atmospheric extinction, however; absorption due to atmospheric oxygen and water vapor are noted in the spectra. Emission lines from atomic nitrogen and oxygen, resulting from dissociation and excitation within the shock layer, have been identified in the spectrum. Atomic carbon and hydrogen as well as CN were also detected, indicating the presence ablation species.

## V. Conclusion

The Hayabusa airborne re-entry observation was a successful international effort: a U.S. mission to document the re-entry of a Japanese spacecraft over an uninhabited region of South Australia. NASA Ames and the SETI Institute led the effort. A team of international researchers on board NASA’s DC-8



**Figure 6. Composite spectrum from the Hayabusa SRC at 13:51:17.27 UTC, approximately 3 seconds prior to peak heating. The spectrum has not been corrected for atmospheric extinction. Several atomic and molecular species have been identified.**

Hayabusa's return was a rare opportunity for NASA to obtain data from an atmospheric entry event. The emission data collected during the observation will provide insight into the aerothermodynamic processes of atmospheric entry and the performance of the capsule's thermal protection system. Atmospheric entry systems for NASA's future exploration missions, such as sample return from Mars, will rely on high fidelity, physics-based design tools validated with relevant ground test and flight data. Validation enables us to build confidence in the use of our design tools, mature their development, and reduce risk in future heat shield designs. The success of this and previous airborne observations confirm the viability of remote observation to support future development initiatives for entry system and hypersonic technologies.

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